IBIS

Quarterly Report

Analysis of Cost: Combustion Flame CVD Diamond Deposition

Contract Number: N00014-93-C2044

IBIS Associates, Inc.
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Executive Summary

IBIS Associates has improved its predictive spreadsheet model of combustion flame chemical vapor deposition (CVD) diamond film fabrication. This report explains the improvements on the combustion flame deposition theory, and shows preliminary results of the economics of this CVD diamond process.

The changes to the model include the incorporation of thermal conductivity as an input to the model, allowing the user to specify the thermal properties of the diamond being formed. Also, the deposition theory in the model has been streamlined with the assistance of diamond deposition experts. Numerous inputs have been eliminated in this process, making the model easier to use.

For this report and the results contained herein, it is assumed that the transport theory model which predicts growth rates in the CVD diamond technical cost model closely predicts actual growth rates for the combustion flame technology and that the input values for variables such as the gas flow rate and substrate diameter are physically achievable.

To be investigated are alternative combustion flame deposition geometries and chemistries. Expert review has revealed that the deposition geometry assumptions (i.e. nozzle:substrate diameter ratio) in the IBIS model may not be optimal for combustion flame deposition. Suggested changes in deposition geometries involve the size, shape, and distance to substrate of the combustion nozzle, as well as higher flow rates at smaller nozzle sizes. Suggested changes in deposition chemistry include using ethylene as the carbon fuel instead of acetylene. Lastly, expert approval of the models is continually in progress.

Combustion Flame TCM Expert Review

The combustion flame CVD diamond Technical Cost Model (in the Appendix) has been reviewed by deposition experts representing Sandia National Laboratories in both Albuquerque, NM and Livermore, CA; Stanford University; Caltech; and Lockheed. Copies of the model were transfered to these theorists along with a non-transferable site license, and all were tutored on the Technical Cost Modeling methodology. A thorough expert review of the combustion flame model was undertaken during this tutorial. In response to the model criticism that surfaced, a plan for the revision of the cost model was drafted.

The expert review of the combustion flame CVD diamond cost model produced no significant criticisms. There was a concensus among the theorists that two of the three quality measures, as reported in the first quarter report for 1994, are unnecessary. The model has been streamlined to use only one of the quality measures (H/CH3), which is believed to correlate the closest to thermal conductivity.

A defect-based model of CVD diamond material properties has been developed by Michael Coltrin at Sandia National Laboratories and David Dandy at Colorado State University. Inputs to this model include the hydrogen (H) and methyl radical (CH3) mole fractions at the growth surface, as well as numerous rate constants for the reactions considered at the growth surface. Outputs of this model include the growth rate and defect density, which are used to determine thermal conductivity. IBIS generated data from this model and performed regression analysis in order to find the H/CH3 ratio as a function of thermal conductivity. As shown later in this report, the relationship assumed to exist between H/CH3 and the thermal conductivity of the CVD diamond allows thermal conductivity to exist as an input to the cost model.

The model's shortcomings were identified by the experts as its inability to predict the effects of changing in reactor pressure, fuel chemistry, or nozzle count. The concensus was reached that a new version of the model should be developed with the ability to predict changes in these three conditions. Due to the large amount of data required to derive predictive relationships for all these processing parameters and the nonexistance of this data in the public domain, a plan for data collection from numerical models was established. As agreed, all organizations involved in the expert review with the exception of Lockheed will cooperate in the data generation.

Sensitivity Analysis

Technical Cost Modeling permits the flexibility of performing sensitivity analyses. Using sensitivity analyses, it is possible to explore the cost implications of changing key input variables such as gas composition, production volume, material prices, product dimensions, etc. As an R&D management tool, these analyses help set development goals for cost effective manufacturing. Further, they help in long term planning, by indicating the cost savings that may be realized through scale-up. For the purpose of these sensitivity analyses it is assumed that the transport theory model which is used to estimate the diamond growth rate closely predicts actual growth rates and that the input values for variables such as gas flow rate and substrate temperature are physically achievable. Presented in the following sections are the following analyses, all based on the assumption of thermal management quality diamond:

- Cost vs Substrate Diameter and Gas Consumption
- Cost vs Thermal Conductivity and Gas Ratio
- Cost vs Thermal Conductivity and Substrate Diameter

For all of these analyses, the ratio of substrate to duct area is held constant. This constraint is due to the geometry assumed for the combustion flame technology as modeled (i.e., a single nozzle torch). The area of the gas duct is the cross-sectional area of the flame before it is affected by the flow pattern around the substrate. For a combustion flame with a corresponding duct area impinging on an infinite plane, there will be a circular region of desirable diamond and a surrounding region of unacceptable diamond. Consider the similar case of a flame impinging on a substrate of the same area. As a substrate diameter increases while the duct diameter remains constant, there is a point at which the substrate extends into this zone of unacceptable diamond. Therefore, there is a maximum substrate:duct area ratio that should not be exceeded. Experts in CVD diamond deposition suggest that this ratio is roughly 3:1 for single nozzle torches. When the substrate diameter is varied in the following analyses, the duct diameter is adjusted so that the ratio of substrate to duct area is constant.

Cost vs Substrate Diameter and Gas Consumption

Figure 1 shows the combustion flame deposition cost per square centimeter of one millimeter thick polycrystalline diamond varying with the diameter of the deposited wafer. In addition, because the duct area and gas flow rate increase with substrate area, Figure 1 shows the total gas flow rate changing with the substrate diameter. The volumetric gas flow rate must change with the duct diameter, if constant quality is to be maintained, due to the assumptions in deposition theory that are mentioned in the first quarter report of 1994. At about nine centimeters in diameter, the cost per square centimeter of combustion flame CVD diamond reaches a minimum of roughly $60. The incorporation of the gas flow rate plot illustrates why there exists an optimum substrate diameter: as the duct area increases to

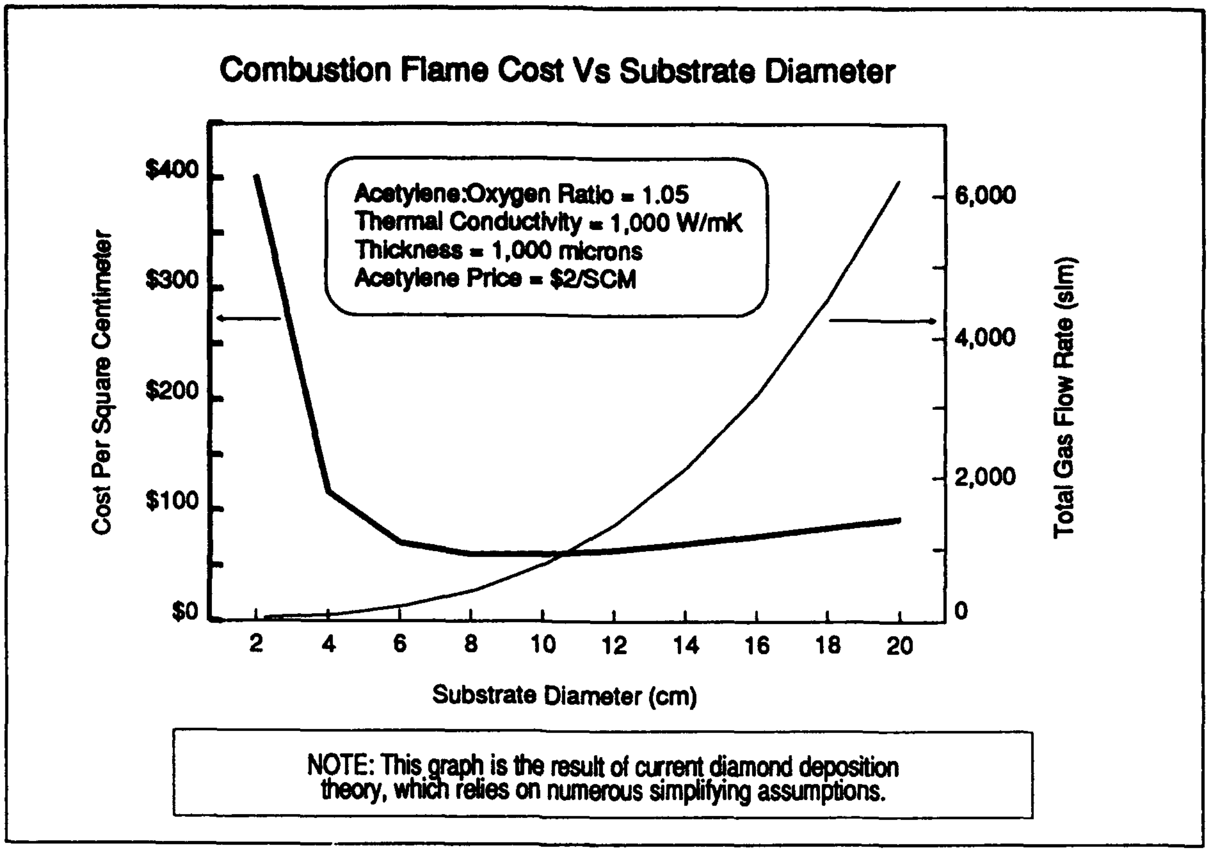
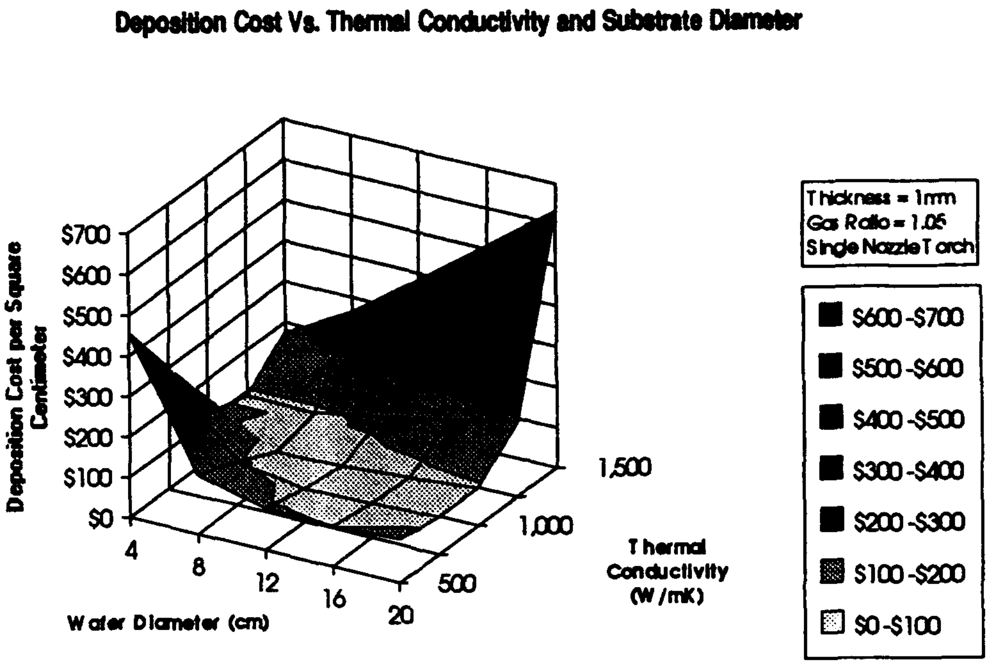


Figure 1

maintain the substrate to duct area ratio, the volumetric gas flow rate must also increase to sustain the same strain rate parameter (same quality diamond). Therefore, the economy of scaling the substrate diameter peaks at about nine centimeters, above which the required gas flow increases the cost.

Cost vs Thermal Conductivity and Gas Ratio

The effect of quality, in terms of thermal conductivity, on CVD diamond deposition cost at different gas ratios can be seen in Figure 2. The reason for the rise in cost with thermal conductivity relates to the correlation between purity and thermal conductivity. For this simulation, the purity of diamond is assumed to depend on the ratio of atomic hydrogen to methyl radicals at the growth surface; this model predicts that thermal conductivity will increase with this ratio. Increasing the ratio of atomic hydrogen to methyl radicals, while keeping the proportion of acetylene to oxygen flow constant, requires an increase in the flow rate of the inlet gases. As shown in Figure 1, increasing flow rates leads to rising costs. From Figure 2, higher thermal conductivity diamond (1,000 to 1,500 W/mK) should be grown at lower ratios of acetylene to oxygen, dropping the cost by a factor of four when lowering this ratio from 1.10 to 1.02 at 1,500 W/mK. Also shown in Figure 2 is the cost of thermal conductivity. CVD diamond grown to achieve 1,000 W/mK thermal conductivity costs about an order of magnitude less than diamond with 1,500 W/mK thermal



NOTE: This graph is the result of current diamond deposition theory, which relies on numerous simplifying assumptions.

Figure 3

Conclusions

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Appendix

Revision Date: 6/30/94

PRODUCT SPECIFICATIONS			
Torch Type	Single Nozzle		
Part Name	6 in. substrate		NAME
Wafer Diameter	15.24	cm	DIAM
Finished Wafer Thickness	1,000	um	THIK
Thermal Conductivity	1,000	W/mK	THERMCON
Annual Production Volume	1.0	(000/yr)	NUM
Length of Production Run	5	yrs	PLIFE
PROCESS RELATED FACTORS - SURFACE PREPARATION			
Process In Use?	1	[1=Y 0=N]	USE1
Dedicated Investment	0	[1=Y 0=N]	DED1
Process Yield	95.0%		YLD1
Average Equipment Downtime	20.0%		DOWN1
Direct Laborers Per Station	0.50		NLAB1
Substrate Material	11	[menu #]	MATL1
Pieces Per Batch	20	pcs/batch	PCS1
Process Time	60.00	min/batch	PTIME1
Building Space Requirement	250	sqft/sta	FLR1
PROCESS RELATED FACTORS - DEPOSITION			
Process In Use?	1	[1=Y 0=N]	USE2
Dedicated Investment	0	[1=Y 0=N]	DED2
Process Yield	87.5%		YLD2
Average Equipment Downtime	15.0%		DOWN2
Direct Laborers	0.40	/sta	NLAB2
Machine Power	2	kW	POW2
Machine Load/Unload Time	120	min/batch	PTIME2
Available Deposition Time	8,640	hrs/yr	DAYHR2
Heat Removal via Substrate	50.0%	of total	HTRMV2
Coolant Temp. Rise	50	C	TEMP2
Heat Capacity of Coolant	1.0	cal/g/C	CP2
Building Space Requirement	1,500	sqft/sta	FLR2
Acetylene:Oxygen Ratio (R)	1.05	[1.02<x<1.1]	GRATIO2
Oxygen	26	[menu #]	GASA2
Acetylene	20	[menu #]	GASB2
Oxygen Recycle Rate	0.0%		RECYC2A
Carrier Gas Recycle Rate	0.0%		RECYC2B
Gas Recycle Equipment Cost	#N/A	total	MCH2A
Growth Correction Factor (f)	0.50		GCF2
Substrate:Duct Area Ratio	3.00	[1<x<=4]	SUBDUC2
Substrate Distance:Duct Diam	1.00	[0<x<=10]	L:D2

PROCESS RELATED FACTORS - ETCHING

COMBUSTION FLAME CVD DIAMOND TECHNICAL COST MODEL - LONG TERM
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GAS DATABASE

#	Gas	Source	Purity	Price $/SCM	No. of Carbons	ɔunt/Mo SCM	Mo.Tank Rental	Price Update
0	None			$0.00	0.00	0E+00		
1	ˌiq Hydrogen	Airco	99.998%	$0.34	0.00	3E+04	$2,070	1/93
2	ˌiq Hydrogen	Airco	99.998%	$0.32	0.00	4E+04	$2,970	1/93
3	ˌiq Hydrogen	Airco	99.998%	$0.30	0.00	1E+05	$4,500	1/93
4	Liq Argon	Airco	99.998%	$1.41	0.00	8E+03	$590	1/93
5	Liq Argon	Airco	99.998%	$1.32	0.00	2E+04	$820	1/93
6	Liq Argon	Airco	99.998%	$1.29	0.00	3E+04	$1,300	1/93
7	Hydrogen	MG Ind.	99.9999%	$29.86	0.00	0E+00		1/93
8	Hydrogen	MG Ind.	99.9996%	$40.61	0.00	0E+00		1/93
9	Hydrogen	MG Ind.	99.999%	$10.28	0.00	0E+00		1/93
10	Hydrogen	Air Prod.	99.95%	$1.59	0.00	0E+00		1/93
11	Argon	MG Ind.	99.9999%	$33.09	0.00	0E+00		1/93
12	Argon	Air Prod.	99.9997%	$37.33	0.00	0E+00		1/93
13	Argon	Air Prod.	99.999%	$11.74	0.00	0E+00		1/93
14	Argon	Air Prod.	99.997%	$2.03	0.00	0E+00		1/93
15	Methane	Air Prod.	99.99%	$21.99	1.00	0E+00		1/93
16	Methane	Air Prod.	99%	$13.76	1.00	0E+00		1/93
17	Methane	Air Prod.	93%	$4.93	1.00	0E+00		1/93
18	Acetylene	Air Prod.	99.6%	$9.70	2.00	0E+00		1/93
19	Acetylene	Air Prod.	98.5%	$5.30	2.00	0E+00		1/93
20	Acetylene	Pipeline	98.5%	$2.00	2.00	0E+00		1/93
21	Helium	Air Prod.	99.9995%	$15.90	0.00	0E+00		1/93
22	Helium	Air Prod.	99.995%	$4.77	0.00	0E+00		1/93
23	Nitrogen	Air Prod.	99.9996%	$45.50	0.00	0E+00		1/93
24	Nitrogen	MG Ind.	99.999%	$9.23	0.00	0E+00		1/93
25	Nitrogen	Air Prod.	99.998%	$1.24	0.00	0E+00		1/93
26	Liq Oxygen	Air Prod.	99.5%	$0.21	0.00	1E+00	$350	1/93
27	Oxygen	Air Prod.	99.5%	$0.58	0.00	0E+00		1/93

SUBSTRATE DATABASE

#	Substrate	Source	Price $/ea	Thick um	Diam cm	Etch um/min	Life use#	Price Update
0	None		$0.00	1	1.00	1.00	1.00	
1	Silicon	Si-Tech	$2.65	1270.00	5.08	20.00	1	1/93
2	Silicon	Si-Tech	$3.50	1270.00	7.62	20.00	1	1/93
3	Silicon	Si-Tech	$6.25	1270.00	10.16	20.00	1	1/93
4	Silicon	Si-Tech	$9.70	1270.00	12.70	20.00	1	1/93
5	Silicon	Si-Tech	$18.60	1270.00	15.24	20.00	1	1/93
6	Silicon	Si-Tech	$57.95	1270.00	20.32	20.00	1	1/93
7	Silicon	Si-Tech	$4.35	3810.00	5.08	20.00	1	1/93
8	Silicon	Si-Tech	$8.15	3810.00	7.62	20.00	1	1/93
9	Silicon	Si-Tech	$14.50	3810.00	10.16	20.00	1	1/93
10	Silicon	Si-Tech	$22.65	3810.00	12.70	20.00	1	1/93

Process In Use?	1	[1=Y 0=N]	USE3
Dedicated Investment	0	[1=Y 0=N]	DED3
Process Yield	99.0%		YLD3
Average Equipment Downtime	10.0%		DOWN3
Direct Laborers Per Station	1.00		NLAB3
Load/Unload and Rinse Time	30.00	min/batch	PTIME3
Pieces Per Batch	20		PCS3
Machine Cost	$6,000	/sta	MCH3
Etchant Cost	$70	/liter	ETCH3A
Etchant Disposal Cost	$30	/liter	ETCH3B
Machine Etchant Capacity	1.00	l/batch	CAP3
Machine Power	0.00	kW	POW3
Building Space Requirement	100	sqft/sta	FLR3
PROCESS RELATED FACTORS - LASER TRIMMING			
Process In Use?	1	[1=Y 0=N]	USE4
Dedicated Investment	0	[1=Y 0=N]	DED4
Process Yield	99.0%		YLD4
Average Equipment Downtime	10.0%		DOWN4
Direct Laborers Per Station	1.00		NLAB4
Machine Cost	$6,000	/sta	MCH4
Trimming Rate	1.00	cm/s	RATE4
Machine Power	0.00	kW	POW4
Building Space Requirement	100	sqft/sta	FLR4
PROCESS RELATED FACTORS - LAPPING			
Process In Use?	1	[1=Y 0=N]	USE5
Dedicated Investment	0	[1=Y 0=N]	DED5
Process Yield	90.0%		YLD5
Average Equipment Downtime	15.0%		DOWN5
Direct Laborers Per Station	1.00		NLAB5
Lapped Material Removal	10.0%	by wgt	TLAP5
No of Lapping Steps	2		LAPS5
Pieces Per Batch	5		PCS5
Load/Unload and Clean Wafers	40.00	min/batch	PTIME5
Average Lapping Rate	1.0	um/hr	RATE5
Lapping Slurry Cost	$53	/liter	LAPSL5
Lapping Slurry Usage Rate	0.50	liter/hr	LAPR5
Lapping Plate Life	320	hrs	PLAL5
Available Lapping Time	8,640	hrs/yr	DAYHR5
Building Space Requirement	400	sqft/sta	FLR5
			/rnd
PROCESS RELATED FACTORS - INSPECTION - MICROSCOPY			
Process In Use?	1	[1=Y 0=N]	USE6
Dedicated Investment	0	[1=Y 0=N]	DED6
Process Yield	95.0%		YLD6
Average Equipment Downtime	5.0%		DOWN6
Direct Laborers Per Station	1.00		NLAB6

11	Silicon	Si-Tech	$43.45	3810.00	15.24	20.00	1	1/93
12	Silicon	Si-Tech	$135.20	3810.00	20.32	20.00	1	1/93
13	Silicon	Si-Tech	$6.85	6350.00	5.08	20.00	1	1/93
14	Silicon	Si-Tech	$12.80	6350.00	7.62	20.00	1	1/93
15	Silicon	Si-Tech	$22.75	6350.00	10.16	20.00	1	1/93
16	Silicon	Si-Tech	$35.55	6350.00	12.70	20.00	1	1/93
17	Silicon	Si-Tech	$68.30	6350.00	15.24	20.00	1	1/93
18	Silicon	Si-Tech	$212.45	6350.00	20.32	20.00	1	1/93
19	Molybdenum	Phil. Elmet	$3.90	254	5.08	10.00	1	1/93
20	Molybdenum	Phil. Elmet	$8.20	254	10.16	10.00	1.00	1/93
21	Molybdenum	Phil. Elmet	$14.50	254	15.24	10.00	1.00	1/93
22	Molybdenum	.logies Corp	$25.35	254	20.32	10.00	1.00	1/93
23	Molybdenum	.logies Corp	$4.80	508.00	5.08	10.00	4	1/93
24	Molybdenum	.logies Corp	$14.75	508.00	10.16	10.00	4	1/93
25	Molybdenum	.logies Corp	$24.30	508.00	15.24	10.00	4	1/93
26	Molybdenum	.logies Corp	$37.10	508.00	20.32	10.00	4	1/93
27	Molybdenum	Phil. Elmet	$9.15	1524.00	5.08	10.00	20	1/93
28	Molybdenum	.logies Corp	$27.60	1524.00	10.16	10.00	20	1/93
29	Molybdenum	.logies Corp	$52.25	1524.00	15.24	10.00	20	1/93
30	Molybdenum	.logies Corp	$85.25	1524.00	20.32	10.00	20	1/93
31	Molybdenum	.logies Corp	$14.75	2286.00	5.08	10.00	32.00	1/93
32	Molybdenum	.logies Corp	$36.00	2286.00	10.16	10.00	32.00	1/93
33	Molybdenum	.logies Corp	$69.00	2286.00	15.24	10.00	32.00	1/93
34	Molybdenum	.logies Corp	$113.50	2286.00	20.32	10.00	32.00	1/93
35	Molybdenum	.logies Corp	$18.50	3175.00	5.08	10.00	46.00	1/93
36	Molybdenum	.logies Corp	$46.75	3175.00	10.16	10.00	46.00	1/93
37	Molybdenum	.logies Corp	$90.50	3175.00	15.24	10.00	46.00	1/93
38	Molybdenum	.logies Corp	$149.00	3175.00	20.32	10.00	46.00	1/93
39	Tungsten	.logies Corp	$7.75	254	5.08	10.00	1	1/93
40	Tungsten	.logies Corp	$24.50	254	10.16	10.00	1.00	1/93
41	Tungsten	.logies Corp	$50.00	254	15.24	10.00	1.00	1/93
42	Tungsten	.logies Corp	$79.25	254	20.32	10.00	1.00	1/93
43	Tungsten	.logies Corp	$10.00	508.00	5.08	10.00	4.00	1/93
44	Tungsten	.logies Corp	$35.10	508.00	10.16	10.00	4.00	1/93
45	Tungsten	.logies Corp	$67.00	508.00	15.24	10.00	4.00	1/93
46	Tungsten	.logies Corp	$109.20	508.00	20.32	10.00	4.00	1/93
47	Tungsten	.logies Corp	$50.00	1524.00	5.08	10.00	20.00	1/93
48	Tungsten	.logies Corp	$112.00	1524.00	10.16	10.00	20.00	1/93
49	Tungsten	.logies Corp	$317.00	1524.00	15.24	10.00	20.00	1/93
50	Tungsten	.logies Corp	$422.00	1524.00	20.32	10.00	20.00	1/93
51	Tungsten	.logies Corp	$60.00	3175.00	5.08	10.00	46.00	1/93
52	Tungsten	.logies Corp	$161.25	3175.00	10.16	10.00	46.00	1/93
53	Tungsten	.logies Corp	$521.30	3175.00	15.24	10.00	46.00	1/93
54	Tungsten	.logies Corp	$687.00	3175.00	20.32	10.00	46.00	1/93
55								
####	############	###########	##########	##########	#########	######	#######	######

Average Inspection Time	15.00	min/batch	PTIME6	
Percent Inspection	100%		INSP6	
Machine Cost	$50,000	/sta	MCH6	
Machine Power	0.10	kW	POW6	
Building Space Requirement	50	sqft/sta	FLR6	

PROCESS RELATED FACTORS - INSPECTION - THERMAL CONDUCTIVITY

Process In Use?	1	[1=Y 0=N]	USE7
Dedicated Investment	0	[1=Y 0=N]	DED7
Process Yield	95.0%		YLD7
Average Equipment Downtime	5.0%		DOWN7
Direct Laborers Per Station	1.00		NLAB7
Average Inspection Time	15.00	min/batch	PTIME7
Percent Inspection	100%		INSP7
Machine Cost	$50,000	/sta	MCH7
Machine Power	0.10	kW	POW7
Building Space Requirement	50	sqft/sta	FLR7

OPTIONAL INPUTS

	override	estimate		
Surface Preparation				
Machine Cost	$0	$65,774	/sta	OMCH1
Machine Power	0.0	19.2	kW	OPOW1
Deposition				
Duct Area	0.00	60.80	sqcm	ODAREA2
Total Gas Flow Rate	0	2,743	slm	OTFLOW2
Deposition Rate	0.00	1.14	g/hr	ODRATE2
Deposition Equipment Cost	$0	$71	k$/sta	OMCH2
Etching				
Process Cycle Time	0.00	0.18	hrs	OCTIME3
Chemical Requirement	$0	$5.00	/pc	OCHEM3
Laser Trimming				
Process Cycle Time	0.00	0.01	hrs	OCTIME4
Lapping				
Lapping Time	0.00	111.11	hrs	OCTIME5
Lapping Plate Cost	$0	$869	/ea	OWHEEL5
Lapping Machine Cost	$0	$11,939	/sta	OMCH5
Lapping Machine Power	0.00	4.2	kW	OPWR5

EXOGENOUS COST FACTORS

Direct Wages	$13.33	/hr	WAGE	
Indirect Salary	$50,000	/yr	SALARY	
Indirect:Direct Labor Ratio	1.00		ILAB	
Benefits on Wage and Salary	35.0%		BENI	
Working Days per Year	360.00		DAYS	
Working Hours per Day (*)	8.00	/hr	HRS	* exc. dep. & lap
Capital Recovery Rate	10%		CRR	
Capital Recovery Period	5.00	yrs	ELIFE	
Building Recovery Life	20.00	yrs	BLIFE	
Working Capital Period	3.00	months	WCP	

Price of Electricity	$0.050	/kWh	ELEC
Price of Natural Gas	$6.50	/MBTU	GAS
Price of Building Space	$100	/sqft	PBLD
Price of Cooling Water	$0.03	/100 gal	WATER
Auxiliary Equipment Cost	15.0%		AUX
Equipment Installation Cost	35.0%		INST
Maintenance Cost	8.0%		MNT

REGRESSION CONSTANTS, COEFFICIENTS, AND EXPONENTS

-Surface Preparation-		
Machine Cost Constant	1,334	MCH1A
Machine Cost Capacity Coef	3,222	MCH1B
Machine Power Constant	-0.75	PWR1A
Machine Power Capacity Coef	1.00	PWR1B
-Deposition-		
Diamond Density (g/cc)	3.52	DENS
[H]/[CH3] Quality Constant	133	QUAL3
[H]/[CH3] Quality Coefficient	164	QUAL3A
[H]/[CH3] Qual. GRatio Exp.	20	QUAL3B
[H]/[CH3] Qual. QMult. Exp.	1.77	QUAL3C
QMult. Coefficient	0.00	QM2A
QMult. Tc Exponent	4.07	QM2B
[H]/[CH3] Qual. Baseline	10.15	QUAL3D
Vol. Expansion Factor Const.	4.76	VEFA2
Vol. Expansion Factor Coeff.1	4.46	VEFB2
Vol. Expansion Factor Coeff.2	-1.83	VEFC2
Growth Rate 10^x Coeff. 3	-3.91	GRA2
Growth Rate "a" Expon. 3	2.91	GRB2
Growth Rate "a2" Expon. 3	-0.39	GRC2
Growth Rate "R" Expon. 3	23.97	GRD2
Growth Rate "R2" Expon. 3	-334.80	GRE2
Enthalpy (kcal/mol) - C2H2	54.19	HF2A
Enthalpy (kcal/mol) - CO	-26.42	HF2B
Machine Cost Wafer Area Coef	161.46	MCH2Y
Machine Cost Area Exponent	1.00	MCH2Z
Machine Cost Area Constant	41,667	MCH2X
-Etching-		
-Lapping-		
Machine Cost Constant	2,719	MCH5A
Machine Cost Capacity Coef	1,844	MCH5B
Machine Power Constant	-0.75	PWR5A
Machine Power Capacity Coef	1.00	PWR5B
Tool Cost Constant	771.00	TOOL5A

Tool Cost Capacity Coef	0.92	TOOL5B
Tool Cost Capacity Exponent	2.90	TOOL5C

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COMBUSTION CVD TCM: SURFACE PREPARATION
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	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$65.66	$65,660	94.1%	
Direct Labor Cost	$0.85	$850	1.2%	
Utility Cost	$0.07	$72	0.1%	
FIXED COST ELEMENTS				
Equipment Cost	$0.65	$647	0.9%	$98,661
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$0.04	$41	0.1%	$25,000
Maintenance Cost	$0.32	$324	0.5%	
Overhead Labor Cost	$0.82	$820	1.2%	
Cost of Capital	$1.36	$1,364	2.0%	
TOTAL FABRICATION COST	$69.78	$69,778	100.0%	$123,661

INTERMEDIATE CALCULATIONS			
Process In Use	1.00	[1=Y 0=N]	PRO1
Cumulative Yield	66.2%		CYLD1
Effective Production Volume	1,511	/yr	ENUM1
Substrate Area	182.4	sq cm	AREA1
New Substrate Cost	$43.45	/pc	SUB1
Substrate Useful Life	1.00	cycle	LIFE1
Process Cycle Time	3	min/pc	CTIME1
Runtime for One Station	3%		RTIME1
Number of Parallel Stations	0.03		NSTAT1
Energy Requirement	0.959	kWh/pc	ENERGY1
Building Space/Station	250	sqft	SPACE1
Machine Cost	$65,774	/sta	MCH1
Machine Power	19.2	kW	POW1
Installed Equipment Cost	$88,795	/sta	IEQUIP1
Auxiliary Equipment Cost	$9,866	/sta	AEQUIP1
Equipment Annuity	$825	/yr	EINT1
Tooling Annuity	$0	/yr	TINT1
Building Annuity	$95	/yr	BINT1
Working Annuity	$68,858	/yr	WINT1

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COMBUSTION CVD TCM: DEPOSITION
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	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$16,730.22	$16,730,220	88.2%	
Direct Labor Cost	$788.29	$788,287	4.2%	
Utility Cost	$60.42	$60,418	0.3%	
FIXED COST ELEMENTS				
Equipment Cost	$270.36	$270,364	1.4%	$1,386,834
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$95.04	$95,038	0.5%	$1,950,000
Maintenance Cost	$260.21	$260,207	1.4%	
Overhead Labor Cost	$253.44	$253,436	1.3%	
Cost of Capital	$501.75	$501,755	2.6%	
TOTAL FABRICATION COST	$18,959.72	$18,959,725	100.0%	$3,336,834
	$103.94	/sqcm		

INTERMEDIATE CALCULATIONS			
Process In Use	1	[1=Y 0=N]	PRO2
Cumulative Yield	69.7%		CYLD2
Effective Production Volume	1,436	/yr	ENUM2
Machine Power	2	kW	DAPOW2
Duct Area (A in.)	60.80	sqcm	DAREA2
Duct Diameter	8.80	cm	DDIAM2
Quality Multiplier	1.07	[0.4<x<5]	QMULT2
Strain Rate (a)	638	1/sec	STRN2A
Volume Expansion Factor	7.42		VOLEF2A
Gas Velocity	5,578	cm/s	SPEED2A
Total Gas Flow Rate	2,743	slm	TFLOW2A
Acetylene Flow Rate	1,405	slm	CFLOW2A
Oxygen Gas Flow Rate	1,338	slm	XFLOW2A
Mass of Diamond Deposited	71.34	g	MASS2
Linear Deposition Rate	17.7	µ/hr	LINDEP2
Mass Deposition Rate	1.1	g/hr	MASDEP2
Deposition Time	62.82	hrs	CTIMEB2
Machine Setup Time	2.00	hrs	CTIMEA2
Runtime for One Station	1267%		RTIME2
Number of Parallel Stations	12.67		NSTAT2
Total Oxygen Gas Volume	5,044	SCM/pc	XGAS2
Total Carbon Gas Volume	5,296	SCM/pc	CARGAS2
Oxygen Gas Cost	$1,059	/pc	COSTA2
Acetylene Gas Cost	$10,592	/pc	COSTB2
Carbon Capture Factor	0.0014%		CCF2
Combustion Enthalpy Change	-447	kJ/mol	ENTH2
Mass Flow of C2H2 and O2	1.87	mol/sec	MFLOW2

Combustion Power	836	kW	CPOW2
Cooling Water Flow Rate	31.7	gal/min	WATER2
Cooling Water Requirement	119,343	gal/pc	COOL2
Energy Requirement	126	kWh/pc	ENERGY2
Building Space/Station	1,500	sqft	SPACE2
Recycle Equipment Cost	$0	/sta	REC2
Liquid Oxygen Tank Rental	$350	/mo/tank	XRENT2
Gas Storage Equipment Rent	$4,200	/year	GTANK2
Machine Cost	$71,120	/sta	MCH2B
Installed Equipment Cost	$96,012	/sta	IEQUIP2
Auxiliary Equipment Cost	$10,668	/sta	AEQUIP2
Equipment Annuity	$344,666	/yr	EINT2
Tooling Annuity	$0	/yr	TINT2
Building Annuity	$220,114	/yr	BINT2
Working Annuity	$18,394,945	/yr	WINT2
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COMBUSTION CVD TCM: ETCHING
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	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$3.98	$3,980	29.0%	
Direct Labor Cost	$4.62	$4,616	33.7%	
Utility Cost	$0.00	$0	0.0%	
FIXED COST ELEMENTS				
Equipment Cost	$0.16	$160	1.2%	$9,000
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$0.04	$45	0.3%	$10,000
Maintenance Cost	$0.14	$135	1.0%	
Overhead Labor Cost	$4.45	$4,452	32.5%	
Cost of Capital	$0.32	$323	2.4%	
TOTAL FABRICATION COST	$13.71	$13,712	100.0%	$19,000

INTERMEDIATE CALCULATIONS

Process In Use	1.00	[1=Y 0=N]	PRO3
Cumulative Yield	79.6%		CYLD3
Effective Production Volume	1,256	/yr	ENUM3
Total Etched Thickness	3,810	um	ETHK3
Average Etchant Rate	20.00	um/min	ERATE3
Process Cycle Time	0.18	hrs/pc	CTIME3
Runtime for One Station	9%		RTIME3
Number of Parallel Stations	0.09		NSTAT3
Chemical Requirement	$5.00	/pc	CHEM3
Energy Requirement	0	kWh/pc	ENERGY3
Building Space/Station	100	sq ft	SPACE3
Installed Equipment Cost	$8,100	/sta	IEQUIP3
Auxiliary Equipment Cost	$900	/sta	AEQUIP3
Equipment Annuity	$204	/yr	EINT3
Tooling Annuity	$0	/yr	TINT3
Building Annuity	$103	/yr	BINT3
Working Annuity	$13,405	/yr	WINT3

COMBUSTION CVD TCM: SER TRIMMING
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	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$0.00	$0	0.0%	
Direct Labor Cost	$0.33	$331	47.8%	
Utility Cost	$0.00	$0	0.0%	
FIXED COST ELEMENTS				
Equipment Cost	$0.01	$11	1.7%	$9,000
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$0.00	$3	0.5%	$10,000
Maintenance Cost	$0.01	$10	1.4%	
Overhead Labor Cost	$0.32	$319	46.1%	
Cost of Capital	$0.02	$18	2.7%	
TOTAL FABRICATION COST	$0.69	$693	100.0%	$19,000

INTERMEDIATE CALCULATIONS

Process In Use	1.00	[1=Y 0=N]	PRO4
Cumulative Yield	80.4%		CYLD4
Effective Production Volume	1,244	/yr	ENUM4
Process Cycle Time	0.01	hrs/pc	CTIME4
Runtime for One Station	1%		RTIME4
Number of Parallel Stations	0.01		NSTAT4
Energy Requirement	0	kWh/pc	ENERGY4
Building Space/Station	100	sq ft	SPACE4
Installed Equipment Cost	$8,100	/sta	IEQUIP4
Auxiliary Equipment Cost	$900	/sta	AEQUIP4
Equipment Annuity	$15	/yr	EINT4
Tooling Annuity	$0	/yr	TINT4
Building Annuity	$7	/yr	BINT4
Working Annuity	$671	/yr	WINT4

COMBUSTION CVD TCM: LAPPING
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	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$725.01	$725,009	43.2%	
Direct Labor Cost	$586.32	$586,316	34.9%	
Utility Cost	$5.79	$5,786	0.3%	
FIXED COST ELEMENTS				
Equipment Cost	$13.50	$13,503	0.8%	$71,634
Tooling Cost	$74.41	$74,415	4.4%	$372,073
Building Cost	$7.54	$7,540	0.4%	$160,000
Maintenance Cost	$17.47	$17,465	1.0%	
Overhead Labor Cost	$188.50	$188,502	11.2%	
Cost of Capital	$59.54	$59,540	3.5%	
TOTAL FABRICATION COST	$1,678.08	$1,678,077	100.0%	$603,707

INTERMEDIATE CALCULATIONS			
Process In Use	1.00	[1=Y 0=N]	PRO5
Cumulative Yield	81.2%		CYLD5
Effective Production Volume	1,231	/yr	ENUM5
Thickness of Material Lapped	111.11	um	HLAP5
Setup Time	1.33	hrs/batch	CTIME5A
Lapping Time	111.11	hrs/batch	CTIME5B
Runtime for One Station	377%		RTIME5
Number of Parallel Stations	3.77		NSTAT5
Lapping Plate Cost	$869	/ea	PLA5
Lapping Plate Life	14	pcs	WHEEL5
Number of Plates Required	428.00		PLAT5
Lapping Slurry Consumption	11.11	l/pc	GRIT5
Machine Power	4.2	kW	PWR5
Energy Requirement	94	kWh/pc	ENERGY5
Machine Cost	$11,939	/sta	MCH5
Building Space/Station	400	sq ft	SPACE5
Installed Equipment Cost	$16,118	/sta	IEQUIP5
Auxiliary Equipment Cost	$1,791	/sta	AEQUIP5
Equipment Annuity	$17,214	/yr	EINT5
Tooling Annuity	$94,865	/yr	TINT5
Building Annuity	$17,463	/yr	BINT5
Working Annuity	$1,548,534	/yr	WINT5

COMBUSTION CVD TCM: INSPECTION - MICROSCOPY
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	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$0.00	$0	0.0%	
Direct Labor Cost	$5.25	$5,249	39.9%	
Utility Cost	$0.00	$1	0.0%	
FIXED COST ELEMENTS				
Equipment Cost	$1.52	$1,519	11.6%	$75,000
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$0.03	$25	0.2%	$5,000
Maintenance Cost	$0.65	$648	4.9%	
Overhead Labor Cost	$5.06	$5,062	38.5%	
Cost of Capital	$0.63	$634	4.8%	
TOTAL FABRICATION COST	$13.14	$13,138	100.0%	$80,000

INTERMEDIATE CALCULATIONS			
Process In Use	1.00	[1=Y 0=N]	PRO6
Cumulative Yield	90.3%		CYLD6
Effective Production Volume	1,108	/yr	ENUM6
Process Cycle Time	0.25	hrs	CTIME6
Runtime for One Station	10%		RTIME6
Number of Parallel Stations	0.10		NSTAT6
Energy Requirement	0	kWh/pc	ENERGY6
Building Space/Station	50	sq ft	SPACE6
Installed Equipment Cost	$67,500	/sta	IEQUIP6
Auxiliary Equipment Cost	$7,500	/sta	AEQUIP6
Equipment Annuity	$1,936	/yr	EINT6
Tooling Annuity	$0	/yr	TINT6
Building Annuity	$59	/yr	BINT6
Working Annuity	$11,143	/yr	WINT6

COMBUSTION CVD TCM: INSPECTION - THERMAL CONDUCTIVITY
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	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$0.00	$0	0.0%	
Direct Labor Cost	$4.99	$4,986	38.7%	
Utility Cost	$0.00	$1	0.0%	
FIXED COST ELEMENTS				
Equipment Cost	$1.52	$1,519	11.8%	$75,000
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$0.03	$25	0.2%	$5,000
Maintenance Cost	$0.65	$648	5.0%	
Overhead Labor Cost	$5.06	$5,062	39.3%	
Cost of Capital	$0.63	$629	4.9%	
TOTAL FABRICATION COST	$12.87	$12,871	100.0%	$80,000

INTERMEDIATE CALCULATIONS

Process In Use	1.00	[1-Y 0-N]	PRO7
Cumulative Yield	95.0%		CYLD7
Effective Production Volume	1,053	/yr	ENUM7
Process Cycle Time	0.25	hrs	CTIME7
Runtime for One Station	10%		RTIME7
Number of Parallel Stations	0.10		NSTAT7
Energy Requirement	0	kWh/pc	ENERGY7
Building Space/Station	50	sq ft	SPACE7
Installed Equipment Cost	$67,500	/sta	IEQUIP7
Auxiliary Equipment Cost	$7,500	/sta	AEQUIP7
Equipment Annuity	$1,936	/yr	EINT7
Tooling Annuity	$0	/yr	TINT7
Building Annuity	$59	/yr	BINT7
Working Annuity	$10,877	/yr	WINT7

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COMBUSTION CVD TCM: COST SUMMARY
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	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$17,524.87	$17,524,870	84.5%	
Direct Labor Cost	$1,390.63	$1,390,635	6.7%	
Utility Cost	$66.28	$66,279	0.3%	
FIXED COST ELEMENTS				
Equipment Cost	$287.72	$287,723	1.4%	$1,725,129
Tooling Cost	$74.41	$74,415	0.4%	$372,073
Building Cost	$102.72	$102,718	0.5%	$2,165,000
Maintenance Cost	$279.44	$279,438	1.3%	
Overhead Labor Cost	$457.65	$457,654	2.2%	
Cost of Capital	$564.26	$564,263	2.7%	
TOTAL FABRICATION COST	$20,747.99	$20,747,994	100.0%	$4,262,202
	$113.74	/sqcm		

SUMMARY INFORMATION

Part Name	6 in. substrate	
Total Direct Laborers	13.70	/shift
Total Floor Space	21,650	sqft
Total Capital Investment	$4.3	MM
Area Cost	$113.74	/sqcm
Cost Per Carat	$64.81	/ct

Operation	Equipment	Material	Labor	Other
Surface Preparation	$1	$66	$2	$2
Deposition	$270	$16,730	$1,042	$917
Etching	$0	$4	$9	$1
Laser Trimming	$0	$0	$1	$0
Lapping	$14	$725	$775	$165
Inspect - Microscopy	$2	$0	$10	$1
Inspect - Thermal Cond'vity	$2	$0	$10	$1
Total	$288	$17,525	$1,848	$1,087
Total =	$20,748			

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